The Genesis and Morphology of Hawaiian Ferruginous Laterite Crusts[1]

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MASSIVE FERRUGINOUS SOIL HORIZONS have been discovered in the profiles of certain Hawaiian soils which have morphological characteristics similar to the ferruginous laterite crusts found in other tropical areas. Likewise, the nature of the soil weathering responsible for these ferruginous horizons bears a great resemblance to that described for other ferruginous horizons. However, the ferruginous soil horizons found in the Hawaiian Islands do not have the hardness which is described for ferruginous crusts in India or Indo-China. In spite of the lack of this degree of hardness the author feels that the Hawaiian soils which have a hard ferruginous surface or near-surface horizon are the equivalent of the ferruginous laterite crust of other tropical regions. It is the purpose of this article to describe the genetic and morphological characteristics of the Hawaiian laterite crusts and to show their similarity to other described laterite crusts.

The original description of a laterite was made by Buchanan (1807), who defined it as a ferruginous indurate clay which is bricklike in nature. Pendleton (1946), a firm follower of Buchanan, has defined a laterite as follows: "Illuvial horizon largely iron oxides, slaglike, cellular or pisolitic structure, and of such a degree of hardness that it may be quarried out and used for building construction." Many of the temples in tropical Asia are built of these laterite materials. Du Preez (1949) has modified Pendleton's definition in that he describes a laterite to be a vesicular, concretionary, cellular, vermicular, slaglike pisolitic or concrete-like mass consisting chiefly of ferric oxides with or without mechanically entangled quartz and minor quantities of alumina and manganese; it is of varying hardness but it is usually easily shattered when struck a sharp blow with a hammer. Du Preez's definition differs from Pendleton's in that it does not require a degree of hardness to meet the requirements of a material suitable for building construction. Botelho da Costa and Lobo Azevedo (1949) have objected to a definition of a laterite which requires the presence of a concretionary ferruginous layer. In general, Du Preez's definition has considerable acceptance.

Sherman (1949) has pointed out that the laterite crust will be the end product of tropical soil weathering under an alternating wet and dry season. He has suggested that under continuous moist soil conditions the ultimate end product of soil weathering in the tropics will probably be a soil rich in alumina. The ferruginous layer which occurs at or near the surface is called a laterite crust in that it is usually a hard sterile soil area. The ferruginous layer may be found below the surface which may have resulted from erosion or by formation over the water table in coarse-textured soils. The ferruginous layer which develops in the fine-textured soils materials forms below the surface and is later exposed by erosion as sterile hard surface soil.

HAWAIIAN LATERITE CRUSTS

Hawaiian soils having hard sterile surfaces have been described by Sherman *et al.*

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(1949). These soils have a surface horizon which is a compacted or vesicular slaglike mass having a very high apparent specific gravity. Some of these areas are covered with a sparse dwarfed vegetation while others are practically barren areas in which the surface soil has a glazed surface with the hardness of a pavement. The high apparent specific gravity is due to presence of large quantities of iron and titanium oxides which make up more than 75 per cent of the soil. The hard sterile ferruginous laterite crusts have been found on the southern and western slopes of the island of Kauai; on the western slope of the main mountain range of Molokai; and on the white trachyte cliffs of West Maui. In every case the areas are found on long slopes in which heavy rainfall is received at the higher elevations while the lower elevations remain very dry. The areas of hard crusts are found just below the lower boundary of the canopy forest.

MORPHOLOGICAL DESCRIPTIONS OF HAWAIIAN LATERITE CRUSTS

Island of Kauai

The hard sterile laterite crusts are found on the southern and western slopes of leeward Kauai. These areas are found on the benches or on broad and more level areas of the long ridges which run from the top of the mountains toward the ocean. The hard surface crusts are found in the transition zone between the shrub vegetation on the lower elevations of the slope and the dense canopy forest cover on the wet higher elevations of the slope. The surface horizon of the crusted areas is a very hard compacted purple silt loam having a very high apparent specific gravity. The volume weight of this layer approaches 3.0 in some cases. This horizon is very hard and it is necessary to use a heavy sharp tool to break the layer. The chipped-off fragments crush readily in one's hand to a very fine graphite-like powder. This powdery material contains small pellets of magnetite. About 30 per cent of the particles are of clay size, but even so this material does not exhibit any evidence of stickiness when wet. The thickness of the crust may vary from 4 to 14 inches.

The hard surface layer is underlain by a yellowish-brown to reddish-brown friable silt loam. There is very little evidence of heavy minerals which were responsible for the high apparent specific gravity of the surface horizon. While this soil has the physical properties of a silt loam, mechanical analysis of the soil showed that more than 60 per cent of the soil particles are of clay size. The thickness of the friable layer ranges from 12 to 36 inches.

The friable layer lies over an impervious surface of an unconformity or an impervious soil horizon. In the former case the material is of different geological formation than the material from which the soil was formed. In the latter case it has not been established whether the impervious soil horizon is related to the soil solum or is the surface of a buried soil. Whether or not this plastic subsoil is related to the soil, it has provided an impervious layer which, apparently, is necessary for the formation of ferruginous laterite crust.

The chemical analysis of a typical Kauai ferruginous laterite crust is given in Table 1. The high content of iron and titanium oxides in the hard crusted surface horizon is characteristic of these soils. The iron oxide exists as hematite, and titanium oxide as anatase.[3] Another characteristic of the analysis of this horizon is the low content of volatile matter. The B horizon has an iron oxide content ranging from 70 to 80 per cent. The iron oxide of this horizon exists as goethite and hematite. The titanium oxide content of this layer is markedly lower than is that of the hard surface horizon. The chemical composition

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TABLE 1
THE CHEMICAL COMPOSITION OF A TYPICAL FERRUGINOUS LATERITE PROFILE. THIS PROFILE IS LOCATED OFF THE KOKEE ROAD ON KAUAI

HORIZON	SiO_2	Al_2O_3	Fe_2O_3	TiO_2
inches	*per cent*	*per cent*	*per cent*	*per cent*
Surface 0–3	10.8	10.7	38.2	19.4
Ferruginous Crust 3–11	3.8	9.9	47.5	25.1
Friable Layer 11–27	5.5	7.6	78.5	7.2
Plastic Clay 27+	22.8	21.7	35.4	3.3

of the impervious horizon is very different from that of the other two horizons. The higher content of both silica and alumina indicates the presence of alumino-silicate clay minerals.

Island of Molokai

The hard, compacted, ferruginous laterite crusts are found on the westerly slopes of the mountain range. The areas of this soil are found in the zone of the open forest, just below the heavier canopy forest of the wetter, higher elevations. These areas are easy to observe because of their distinct purple color and shiny glazed surfaces. The hard surface layers of these laterite crusts are harder and more compacted than are those found on Kauai. The areas of this soil are limited to a very narrow belt on Molokai, whereas the laterite crusts are found over a much wider area on Kauai. The hard surface crust of these soils is very similar to those found on Kauai. The chief profile difference occurs in the friable layer. The friable layer below the hard surface horizon of the Molokai laterite crusts is very thin, ranging from 4 to 8 inches. In every observed instance the friable layer lies over a solid rock formation.

The physical and chemical compositions of the Molokai laterite crusts are very similar to those of the Kauai laterite crusts. The iron oxide content of the surface ranges from 48 to 65 per cent and the titanium oxide from 20 to 24 per cent. Likewise, the volatile matter ranges from 3.2 to 4.2 per cent. The iron oxide content of the friable layer ranges from 70 to 76 per cent.

West Maui

The ferruginous laterite crusts of West Maui occur as erosion remnants on the white trachyte cliffs. These areas are easily seen from an airplane. From the highway these areas can be seen as red caps on top of the grayish-white ridges running up the mountain slope. These areas are so badly eroded that in only a few locations does the profile remain intact. In one case the hard surface crust has slid away from its friable layer and the two now exist as separate erosion remnants.

The hard surface horizon is a compacted, reddish silt loam having a high apparent specific gravity but lower than that found for Kauai and Molokai laterite crusts. The surface of these crusts is hard but does not have the shiny glazed surface of the two other areas. The clay content of this horizon is higher, being more than 35 per cent.

The friable layer of these soils has all the characteristics of the Kauai profile. It is very ferruginous and has a clay content exceeding 65 per cent. The thickness of the friable layer has been found to range from 12 to 30 inches.

TABLE 2
THE CHEMICAL COMPOSITION OF TYPICAL HAWAIIAN FERRUGINOUS LATERITES AND SIAM FERRUGINOUS LATERITES*

LOCATION OF FERRUGINOUS LATERITE	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	TOTAL
	per cent	*per cent*	*per cent*	*per cent*	*per cent*
Kauai—Waimea Canyon	3.9	5.8	60.8	26.0	96.5
Molokai—Just below forest line	7.8	3.6	60.4	24.0	95.8
Maui—From eroded trachyte cliffs	5.8	12.0	64.8	11.2	93.8
Siam—Ferruginous concretion	11.8	30.0	46.2	1.8	89.8
Siam—Ferruginous lens	15.4	24.8	51.2	2.4	93.8

*Samples of Siam ferruginous laterites were given to the author by Dr. R. L. Pendleton. The sample analyzed was from a portion of the specimen showing the greatest evidence of iron deposition.

These soils have developed from the trachyte rock on which they are found. Even though these are residual soils, there is a sharp boundary between the unweathered trachyte rock and the soil solum.

The chemical composition of the ferruginous laterite crust from West Maui is given in Table 2, along with the analysis of ferruginous laterite horizons from Kauai and Molokai. Also included in Table 2 are samples of Siam laterites. The difference in the analyses indicates that Siam is not as old as the areas on Molokai and Kauai, or that the difference may be due to the nature of the more acidic parent material. Some of the crusts which occur at inaccessible higher elevations appear to have progressed further in their development than those at the accessible lower elevations.

SOIL WEATHERING CYCLE INVOLVED IN FERRUGINOUS LATERITE CRUST FORMATION

The ferruginous laterite crusts have developed in Hawaii under certain definite weathering conditions. It has been pointed out that the ferruginous laterite crusts have formed on long slopes which have a heavy annual rainfall region at the higher elevations and a low annual rainfall at the lower elevations. Certain other characteristics always appear to be necessary for the crust formation. The impervious layer, whether an unconformity or impervious clay layer, is always found below the friable horizon. If one examines the lower portion of the friable layer, indications of the lateral movement of water will be observed. This has been substantiated by the very wet condition found in this layer at a period of several days after heavy rainfalls at the higher elevations. The lateral movement of water through the friable layer has been demonstrated by the seepage of water into wells dug in this type of a soil. The hard crust surfaces are formed in areas of the slope which are either a bench or the more level areas of the slope. The last condition, a very important one, is that the crusts are formed in a climatic region which has a very dry season alternating with a wet season. The greatest development occurs in the regions where the wet and dry seasons are of about the same duration. A typical case would be 4 months with less than 2⅜ inches of rainfall and 3 months having more than 4 inches of rainfall. Some of the dry months may have less than an inch of rainfall; thus, the vegetation of the area will be the type which falls between the shrub vegetation of the drier areas and the tropical canopy forest of the wetter areas.

The two factors which appear to be most responsible for the development of the crusted surface horizons are the lateral movement of water through the friable layer and the alternating wet and dry season. The water moving laterally through the friable layer would contain dissolved ions from the weathering of the soils under a heavy rainfall condition where the soil solum is continuously moist. Sherman (1949) has shown that in these soils iron oxides are being reduced and are being leached away in the percolating water. He also pointed out that titanium content of these wet soils is low as compared to other Hawaiian soils. Thus it is possible for the percolating waters of these soils to contain iron in a reduced form and titanium as a hydrated titanium oxide or in an acid form. The former has been identified by Doelter (1913) in laterite soils, and the latter is possibly due to the very acid condition of the soils of the very wet locations. The waters would also contain a small amount of dissolved silica. The greater portion of the silica is removed during the earlier stages of soil weathering and when the internal drainage of the soil profile was good. As the soil matured, the internal drainage became poor due to the development of impervious clay layers. With the development of the poor internal drainage more of the percolating water will move down the slope laterally and less will percolate through the soil and its weathered parent material. When the lateral movement of percolating water reaches areas having an alternating wet and dry season, conditions become favorable for the capillary rise of the percolating waters during the dry season. The capillary rise of the percolating waters to the surface is greatly enhanced by the benches or level areas of the slopes. A similar case of enrichment of soils of lower elevations by lateral movement of percolating waters has been proposed by Green (1947).

The dissolved iron and titanium are brought to the surface in the capillary water. The iron is stabilized by its oxidation to the ferric form. During the dry season the iron oxide, which probably exists as goethite, and the hydrated titanium oxides are dehydrated to form the minerals hematite and anatase, respectively. The dissolved silica in the percolating waters would probably rise to the very surface before dehydration. The data in Table 1 would support this hypothesis. The lack of an appreciable amount of titanium oxide in the friable layer would suggest that the titanium must move as a colloidal hydrated titanium oxide. Fujimoto *et al.* (1949) have reported the titanium oxide content of 45 per cent in the colloidal fraction of the transitional zone between the friable layer and the laterite crust horizon. The low content of volatile matter, which would include water of hydration, suggests that both titanium and iron oxides are stabilized by dehydration. This would account for the presence of the two secondary minerals hematite and anatase in the surface soil. The ilmenite content of these soil horizons is extremely low and would rule out the possibility of residual concentration. Furthermore, if ilmenite did not decompose under tropical soil weathering, titanium should be concentrated in greater quantities in the surface horizon of the soils developed in the regions of heavy rainfall as well as where it is found in the area having the hard surface crusts. The chemical analyses of these soils do not reveal a concentration of titanium. In Figures 1 and 2 are given the graphical representation of the manner in which the ferruginous laterite crusts have become the zone of accumulation of iron and titanium oxides.

The ferruginous laterite crust is considered to be the senile stage of tropical soil weathering under a climate having alternating wet and dry seasons. Thus as the crust area becomes denuded of vegetation it will remain a stabilized land form until removed by erosion or degraded into another condition by general advancement of age of the general land area. The laterite crusts are very suscep-

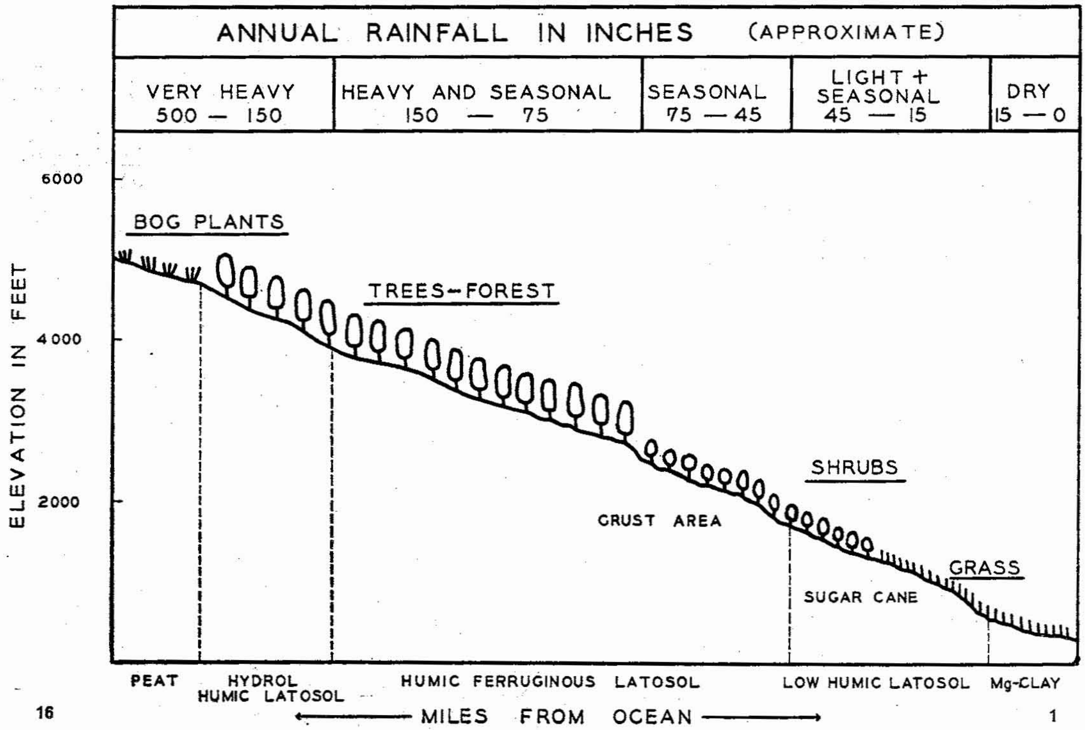

FIG. 1. The location of the ferruginous soils in relation to rainfall distribution, elevation, and vegetation zones.

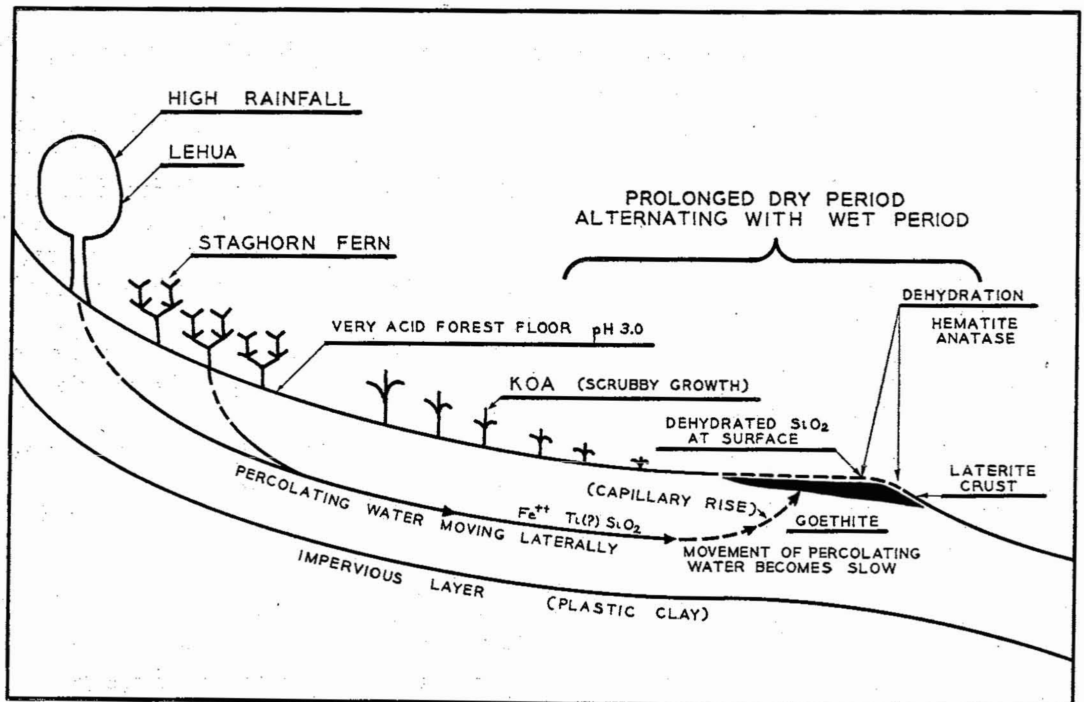

FIG. 2. The location of the ferruginous laterite crust in relation to lateral movement of water from wetter higher elevations.

TABLE 3
THE CHEMICAL COMPOSITION OF A DEGRADED FERRUGINOUS LATERITE PROFILE FROM LIHUE, KAUAI

HORIZON	SiO_2	Al_2O_3	Fe_2O_3	TiO_2
inches	*per cent*	*per cent*	*per cent*	*per cent*
Former ferruginous crust 6–18	28.5	25.8	9.9	24.4
Former friable layer 22–30	32.0	33.2	13.4	7.6

tible to erosion due to the underlying friable layer. Any break in the crust will permit the initiation of erosion by the removal of the friable soil, thus undermining the hard surface layer. Eventually fragments of the hard surface layer will break off. Erosion will eat rapidly into an area and soon only remnants of the original hard surface will remain. The area found on the white trachyte cliffs of West Maui is a good example of this type of erosion.

When the laterite crust is developed in an area which is becoming nearly a peneplain, that area will undergo degradation. In this case the internal drainage becomes restricted and the soil solum is moist or saturated with water during most of the year. Under these conditions the free iron oxides become unstable and are reduced and leached away in the sluggish percolating waters. Titanium oxide will remain quite stable. The profile becomes enriched with colloidal materials and silica from the slow-moving ground waters of the higher elevations. Thus resilication will take place giving rise to a skeleton crust which is rich in silica, alumina, and titanium oxide and low in iron oxide. A typical analysis of a degraded laterite crust is given in Table 3. The data show an iron oxide content of 9.9 per cent and a titanium oxide content of 24.4 per cent in the surface layer of this former ferruginous laterite crust.

SUMMARY

The ferruginous laterite crust has developed in three general areas of the Hawaiian Islands; namely, the southern and western slopes of leeward Kauai; the westerly slopes of the main mountain range of Molokai; and on the white trachyte cliffs of West Maui. The ferruginous laterite crusts are found on the long slopes which have a region of very high rainfall at the higher elevations and a semi-arid condition at the lower elevations. The areas of ferruginous laterite crusts are located at higher elevations which have a definite alternating wet and dry season.

The ferruginous laterite crust profiles have a hard slaglike surface horizon having a very high apparent specific gravity. This layer is underlain by a friable layer of a thickness varying from 4 to 36 inches. This always lies over an impervious layer of either rock or a plastic clay. The hard surface horizon is rich in iron and titanium oxides and very low in volatile matter. The friable layer is made up of iron oxides, which sometimes constitute as much as 80 per cent of the soil.

A hypothesis is advanced as to the genesis of these ferruginous laterite crusts. This proposes that iron and hydrated titanium oxides in the percolating waters from the soils developed on the wet areas of the higher elevations move laterally over the impervious subsoil layers and subsequently accumulate in the surface horizon by capillary action in regions having an alternating wet and dry season climate. The hydrated iron oxide and titanium oxides are stabilized by dehydration and are converted to hematite and anatase in the surface horizon. This gives rise to a

hard compacted surface horizon with a very high apparent specific gravity.

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